Operational energy use versus LCA: case study The Mobble for the Solar Decathlon Europe 2019 competition

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Abstract:
Studies have shown that the building sector is the biggest contributor to global warming, generating 40 to 50 % of the global output of greenhouse gas emissions. Furthermore, this industry consumes up to 40 % of the materials entering the global economy and produces one third of the total waste. In Belgium alone, estimations put the building sector's waste output at fifteen million ton of construction waste on a yearly basis. Therefore, a more environmental-friendly thinking is required, that also considers the impact of construction materials on the environment. For highly insulated buildings the environmental impact of additional construction materials might supersede the reduction in energy use that can be obtained throughout its service life. A trade-off should be made between the embedded and operational energy. For the Solar Decathlon competition 2019 in Szentendre an energy efficient house The Mobble was designed and built, for which detailed dynamic energy simulations were performed in Modelica/Dymola, and as well, a life cycle assessment was done using the simulation software Simapro. Even so, the potential of Personal Comfort Systems (PCS) is investigated through the energy simulations. The result of the trade-off for this case-study shows on the one hand a clear potential of advanced demand control HVAC systems and on the other hand clear limits to the increase of insulation thickness. However, for this specific case it was shown that the optimal insulation thickness from environmental point of view is still well above the minimum requirement in the Belgian building code, even for very efficient HVAC systems.

Keywords:
Energy use, LCA, Embedded energy, Case-study, Personal heating

1. Introduction

A student team from Ghent University took part in the Solar Decathlon Europe 2019 competition in Hungary. The Solar Decathlon competition is an international competition for students at an academic level. Universities from all over the world are being challenged to design, build and operate a sustainable and energy efficient pavilion. Studies have shown that the building sector is the biggest contributor to global warming, generating 40 to 50 % of the global output of greenhouse gas emissions. Further, this industry consumes up to 40 % of the materials entering the global economy and produces one third of the total waste. In Belgium alone, estimations put the building sector's waste output at fifteen million ton of construction waste on a yearly basis [1] [2]. Therefore, a more environmental-friendly thinking is required, that also considers the impact of construction materials on the environment. For highly insulated buildings the environmental impact of additional construction materials might supersede the reduction in energy use that can be obtained throughout its service life.

The following question arises: what is the tipping point between the reduction of operational energy of a building and the increased embedded energy. In this paper a trade-off is made between operational energy use and embedded energy for the participating team pavilion 'The Mobble' in the Solar Decathlon Europe 2019 competition.

2. Case study: The Mobble

The dwelling designed and selected for the Solar Decathlon Europe 2019 competition is used as a case-study project to investigate the trade-off between the environmental impact of embedded and operational energy. The building consists of 5 identical modules, dimensions 2.4m x 6m, which are connected and form 1 dwelling with a rather low compactness of 1,2.

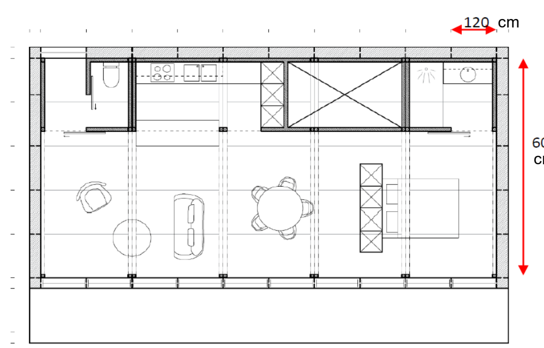

Fig 1: Floor plan of The Mobble [3]

Prefabricated panels are used for the walls, floor and roof. The building parameters are listed in Table 1.

Table 1: Building parameters of the Mobble

Building element	Area [m²]	Thermal transmittance U [W/m²K]
Walls	77,11	0,115
Floor	82,55	0,152
Roof	82,55	0,153
Glazing	27,58	0,7 (triple)
Window frame	3,06	0,7

3. Methodology

First of all, an insight in the operational energy use of the case study is required. Hence, dynamic energy simulations are executed in Modelica/Dymola for both constantly working and demand based HVAC systems. Of course, comfort is a crucial parameter for an indoor environment. Lowering the comfort level in order to save energy in the operational phase is therefore not an option. In literature no consensus is found on the optimal indoor air temperature. As a consequence, the optimal indoor temperature is strongly dependent on which comfort theory – theory of Fanger [4], Zhang [5], … – is adopted. Indoor air temperatures of 20°C and 26°C are chosen for winter and summer respectively, as an acceptable indoor climate and HVAC setpoint. However, during the heating season the indoor temperature of 20°C can be lowered whilst preserving comfort if compensated by Personal Comfort Systems (PCS). Please refer to [6] for more information concerning thermal comfort analysis and PCS for this specific case-study. During the cooling season, the indoor air temperature of 26°C can be increased whilst preserving thermal comfort by adding personal cooling. However, the practical applications of personal cooling are proven to be difficult for a simple reason: comfort issues in summer are related to activities that entail a high metabolism. People typically have a high metabolism while walking around. Therefore, the personal cooling should be mobile and thus integrated in the clothing. However, fans are proven to be the most effective personal cooling devices since the head is the area to tackle and thus the practical applicability of personal cooling is not self-evident. Hence, personal cooling is not included in the energy simulations. To reduce the cooling load, passive measures are taken such as a canopy and sun screens. The remaining cooling load is actively cooled to an indoor temperature of 26°C.

The human comfort simulations have been done in Human Thermal Module, a software of producer Thermo Analytics [7]. This resulted in heat inputs for the local devices as listed in Table 2. The chosen local heating device is a heated chair. As can be seen in Table 2 PCS have their limitations: if the operative temperature is 14 °C, no heated chair can provide enough heat in order to guarantee the comfort of the user, here a single working male. Hence, all simulations with an operative temperature of 14°C and 15°C do not render adequate comfort and are not considered in further analysis.

Table 2: Heat inputs for a heated chair to provide in comfort for various room temperatures

Metabolic rate [met]	Heat input local device per operative temperature [W]						
	20 °C	19	18	17	16	15	14
1.0	0	30	45	60	85	-	-
1.2	0	5	22	50	85	125	-

Subsequently, this operational primary energy use for the combination of PCS and room heating serves as input parameter in the Life Cycle Assessment (LCA), executed in SimaPro using the ReCiPe method [8]. This method considers 18 different environmental performance indices. For the inventory of the data, the Ecoinvent database version 3.5 is used taking a service life of 60 years into account. Although 'The Mobble' is a circular and modular concept, the end-of-life is not taken into account due to the severe uncertainties. A 'Cradle-to-use' approach is chosen, taking into account the production and extraction of materials, transportation to the site and the usage phase by implementing the operational energy from the Dymola/Modelica simulations. Replacements are also accounted for by increasing the amount of material needed, considering a service life of 15 years for finishing layers and 60 years for structural elements. The wall panels have a service life assigned of 30 years due to the modular and circular concept. Note that the LCA of HVAC systems and PCS was not included here.

The combination of LCA and dynamic energy simulations allow a comparison between the environmental impact of the operational energy of the dwelling and the embedded energy of the materials used. Several iterations are done to search for an optimum between the reduction in operational energy use and the increase of embedded energy due to more material-intensive solutions (wall thickness, triple glazing). The configuration in section 2 is referred to as baseline scenario. Next to the baseline, three adaptions are examined. In 'Adaptation 1' the wall panels are insulated with 22 cm of insulation resulting in an increased thermal transmittance of 0,155 W/m²K. In 'Adaptation 2' the window façade has double glazing (U_g = 1,0 W/m²K) instead of triple glazing. In 'Adaptation 3' the wall panels are insulated with 12 cm of mineral wool resulting in a thermal transmittance of 0,27 W/m²K, which is no longer allowed according to the Belgian building code. The three adaptations relative to the baseline were chosen to investigate the balance between operational and embedded energy.

4. Results and discussions

The annual primary energy use for room heating is shown in Fig 2. Evidently the baseline scenario (triple glazing and 30 cm of insulation in the wall panels) has the lowest energy demand for heating. The primary energy use increases for 22 cm of wall insulation (adaptation 1). By replacing the triple glazing by double glazing (adaptation 2) the heating demand and primary energy use will further increase, and finally reducing the insulation package to 12 cm will result in the highest primary energy use. The primary energy use will decrease by lowering the setpoint temperature of the room heating. If the operative temperature of the room heating is lowered from 20°C to 16°C, a reduction in primary energy use for room heating of 40% is obtained (note that the energy use for the PCS to achieve similar comfort is not accounted for).

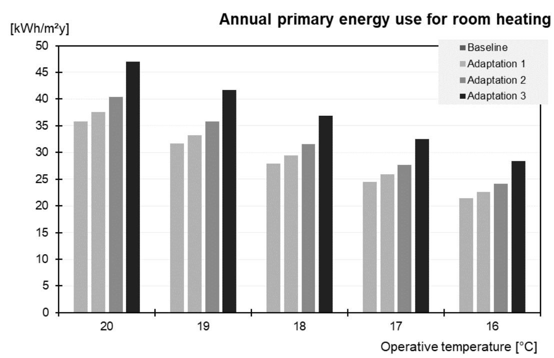

Fig 2: Annual primary energy consumption for room heating (constant temperature)

Considering the total primary energy use of room heating, cooling and personal heating, only a 25% cut in primary energy use can be obtained by lowering the operative temperature from 20°C to 16°C. This is a logical decrease in saving potential because lowering the operative temperature for room heating entails an increased primary energy use for the PCS (Fig 3).

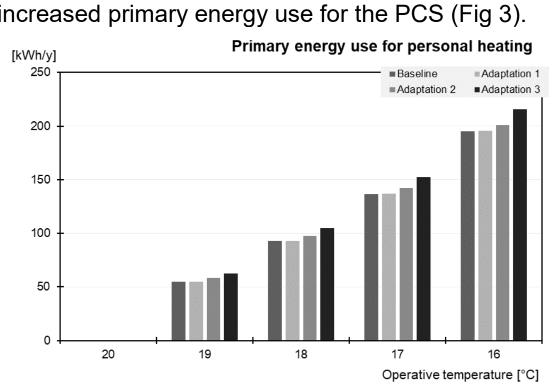

Fig 3: Primary energy use for a heated chair for various operative temperatures (constant HVAC)

If the room temperature does not have to be maintained 24/7 and can be lowered to e.g. 10°C while the dwelling is not occupied, a reduction potential of 17% in primary energy use is found for the simulated user pattern of a working inhabitant.

The trade-off between the total annual primary energy use (heating, cooling, PCS) and embedded energy is shown in Fig 4.

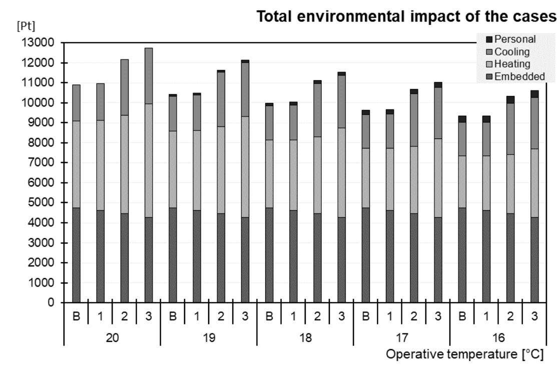

Fig 4: Total environmental impact of the scenarios for varied operative temperatures (constant HVAC)

Again two opposing forces come into play, i.e. the operational phase and embedded energy. On the one hand, lowering the operative temperature results in a decrease in environmental impact due to the saving in total primary energy use of 25%. However, the total environmental impact only decreases by 14%. This can be explained by the low compactness of the case-study. The compactness of a building is defined as the ratio between the volume and the heat loss surface area. A building with a low compactness consequently has a large heat loss surface area and hence a larger material intensity than a highly compact building. On the other hand, Figure 4 shows an increase in environmental impact when the operational energy increases. The increase in operational energy is a result of building components with higher thermal transmittance, resulting in a decreased embedded energy (lower material use). However, the dominance of the operational phase cannot be generalised. Fig. 5 visualizes the contribution of both operational and embedded energy to the total environmental impact of the dwelling.

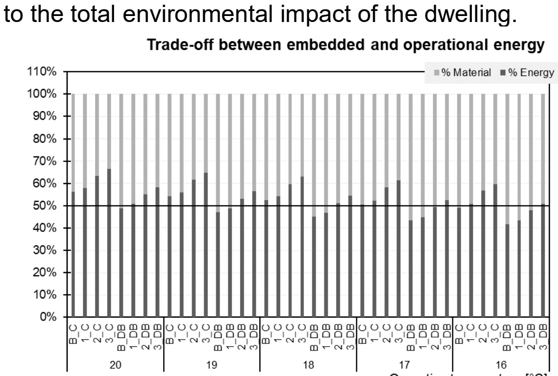

Fig 5: Trade-off between embedded and operational energy (B: baseline, 1-3: adaptation 1-3, C: Constant HVAC, DB: Demand based HVAC)

The question now arises, what is the optimal insulation thickness to minimalize the combination of embedded and operational energy. The result of this optimisation is shown in Fig 6.

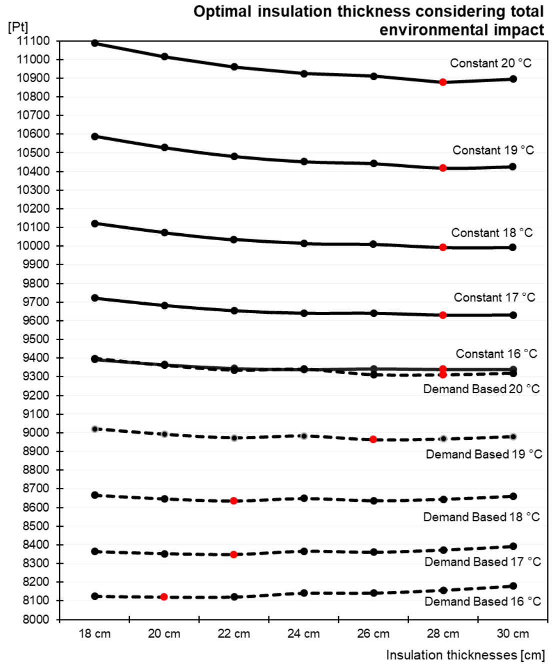

Fig 6: Total environmental impact of insulation thicknesses ranging from 18 cm to 30 cm

For constant heating systems, the optimum insulation thickness from an environmental perspective for operative temperatures ranging from 20°C to 16°C is 28 cm of mineral wool (Fig 6). The energy reduction by using 30 cm instead of 28 cm is only 0,3 %. Thus, the additional 2 cm of insulation material and wood stud size takes more energy to produce. When considering the balance between embedded and operational energy, there is a clear upper limit to the insulation thickness for this case. For demand based systems, the optimum insulation thickness from an environmental perspective for operative temperatures 20°C, 19°C, 18°C, 17°C and 16°C are respectively 28 cm, 26 cm, 22 cm, 22 cm and 20 cm of mineral wool (Fig 6). As there is an upper limit to the insulation thickness, there is also a minimal insulation thickness in this case.

5. Conclusions and outlook

The aim of the research was to investigate whether the environmental impact of additional construction materials might supersede the reduction in energy use that can be obtained throughout its service life. Various influences have been investigated, such as the influence of a constantly working and a demand based HVAC system. Furthermore, the influence of implementing personal heating in order to allow a reduction in operative room temperature to save energy while maintaining comfort was assessed. It can be stated that there are indeed constraints to adding additional construction materials to reduce the operational energy when considering the total environmental impact of the dwelling. When personal heating is not implemented – which is the case for an operative temperature of 20°C – for both the constant and demand based system wall panels with an insulation thickness of 28 cm are most beneficial. The personal heating has the most potential in combination with a demand based system for room conditioning. Here the insulation thickness can be decreased to 20 cm with an operative temperature of 16°C without depriving in comfort. This proves the potential of personal heating systems for reducing the environmental impact of a dwelling. As PCS can be considered as the most efficient demand control HVAC system, for this specific case the increase in system efficiency leads to a reduction around 30% in thermal resistance to achieve the lowest environmental impact. This highlights the susceptibility of LCA assessment towards HVAC efficiency. This research has been focused on one specific user profile, one specific personal heating device, and one specific building. More research on other configurations is required to extrapolate results to building stock level.

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